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DESIGN AND TESTING OF A HIGH-HEAT-FLUX ELECTRON-BOMBARDMENT HEATER

by

R. D. Carlson and R. E. Holtz

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Reactor Engineering Division

March 1968

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NOMENCLATURE

a	Constant in Richardson's Equation	$Amp/cm^2 {}^\circ C^2$
B	Function of r_c/r_a	-
b	Constant in Richardson's Equation	°C
e	Napierian base	-
$E(r)$	Field strength	V/cm^2
f_c	Filamentary cathode correction factor	-
G	Perveance	-
I	Diode current	Amp
i	Diode current density	Amp/cm^2
L	Cathode length	cm
P	Power	W
$q_{c \rightleftarrows a}$	Thermal-radiation heat transfer between cathode and anode	-
r	Radius	cm
r_a	Anode radius	cm
r_c	Cathode radius	cm
r_g	Grid radius	cm
s	Cathode spacing	cm
T	Temperature	°C
T_a	Anode temperature	°C
T_c	Cathode temperature	°C
V_a	Anode voltage	V
V_g	Grid-bias voltage	V
V_{co}	Cutoff voltage	V
β_{ca}	Cathode-anode radius function	-
β_{cg}	Cathode-grid radius function	-
μ	Amplification factor	-

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ABSTRACT

The applications of electron-bombardment heating to liquid-metal heat transfer and reactor safety experiments are discussed. Space-charge-limited heater operation with both triode and diode concepts and emission-limited heater operation are evaluated. The design of a high-heat-flux, electron-bombardment heater (EBH) is presented.

The operating results of the high-heat-flux EBH are presented. Heat fluxes ranging beyond 2.5×10^6 Btu/hr-ft^2 were obtained. Long periods of EBH operation at high heat fluxes were achieved. Curves showing the operating characteristics of the high-heat-flux EBH are also presented.

I. INTRODUCTION

One of the more severe problems involved in obtaining experimental heat-transfer information pertinent to general reactor technology and fast-reactor safety-analysis techniques is the design and construction of a satisfactory heated section. Heat fluxes well above 10^6 Btu/hr-ft^2 (perhaps up to 10^7 Btu/hr-ft^2) may be required for studying the vaporization characteristics of the liquid metals. Many of the difficulties arise from the inability of heater sections to function properly. Most of these heater difficulties have been caused by material-expansion problems at higher temperatures.

Different heating techniques have been applied in various heat-transfer experiments involving liquid metals. This report examines electron-bombardment-heating techniques in detail. Design information and experimental results pertinent to the operation of a high-heat-flux electron-bombardment heater, which can operate in both the space-charge-limited region and the emission-limited region, will be presented and evaluated.

Considerable information has been published about liquid vaporization in various systems. Much of this information has been in the form of empirical results for use in boiling-water systems. Because of a growing interest in the safety aspects of fast reactors and in boiling-liquid technology, recent efforts have attempted to supply information concerning the vaporization characteristics of the liquid metals, especially the alkali metals. Vaporization experiments with water have taken place at temperatures relatively low when compared with the temperatures encountered during similar tests with liquid metals.

In boiling-water studies, a tube containing the water is often resistance-heated. The generated heat flows from the metal tube to the water. An insignificant amount of heat is generated in the water because the electrical resistivity of the water is large compared with that of the metal tube. However, this heating technique is not applicable in experiments dealing with liquid-metal heat transfer because the electrical resistivity of the liquid metal is approximately of the same order of magnitude as that of the containing walls. Different heating techniques must be used so that little or no heat is generated in the liquid metals, thus providing a technique for simulating reactor fuel elements.

Some of the techniques presently being considered for investigations of boiling-liquid-metal heat transfer are:

1. Modified resistance heating.
2. Induction heating.
3. Binary-system heating.
4. Thermal-radiation heating.
5. Electron-bombardment heating.

The application of these heating techniques is summarized in Ref. 1.

II. EBH BACKGROUND INFORMATION

Electron-bombardment heating may be used for supplying heat to various out-of-pile tests which simulate reactor coolant dynamics. Taylor and Steinhaus[2] have shown, during EBH tests with water, that electron-bombardment heating is a satisfactory heating technique for both initially static and flowing systems. More recent investigations[3,4] have used electron-bombardment heating to supply heat to liquid-metal experiments.

Electron-bombardment heating may be used in a system studying annular flow, flow through a tube, or flow through rod clusters. The basic system for coolant-dynamics testing in annular flow consists of two concentric tubes with heat applied to the inside surface of the inner tube while the liquid metal flows in the annulus between the tubes. The heating is accomplished by placing an electron emitter (cathode) inside the evacuated inner tube (anode), heating the cathode, and drawing the electrons to the anode with an accelerating voltage. The generated heat then flows through the tube wall to the liquid metal inside the annulus. EBH tests supplying heat to sodium contained in an annulus have been conducted.[4]

The arrangement for using an EBH to supply heat to a liquid metal flowing inside a circular tube consists of the electron emitters (cathode) surrounding a flow tube (anode). The cathode may consist of many vertically positioned wires, equally spaced around the flow tube. The electrons are drawn from the emitters to the outside tube wall, and the heat generated at the outside tube wall is conducted through the tube to the liquid metal. This EBH arrangement must be surrounded by radiation shields, which are at the same potential as the cathode. The EBH discussed in this report is of this type.

When electron-bombardment heating is used, for studying coolant flow through clusters, a group of heaters similar to those for studying flow through an annular section may be employed. These heaters may be positioned to obtain the desired geometrical configurations.

Initially, a small-scale electron-bombardment heating model was constructed at Argonne to verify the uniform heat fluxes expected. This model consisted of a 0.020-in.-diam, uncarborized, thoriated-tungsten filament wire (cathode) inside a 0.5-in.-OD, Type 316 stainless steel tube (anode) of a 0.035-in. wall thickness. The heated length was 4 in. Chromel-Alumel thermocouples were placed 0.5 in. from both ends of the heated length and in the center of the anode on the outside surface. During heater operation, the thermocouple at the center of the anode and the thermocouples at the ends gave identical temperature readings at various heat fluxes. Heat fluxes up to approximately 800 Btu/hr-ft^2 at the outside anode surface were obtained. Limitations of the available power supply caused the termination of testing at these power levels.

To gain experience with electron-bombardment heating at higher power levels than the previous experiment allowed and to check out the high-voltage power supply required, another experiment was designed. This system had a wire cathode placed inside a vertical tube (anode) with liquid sodium surrounding the tube.[4] The system, shown schematically in Fig. 1, has a 16-in. heated length. The tubular anode was a 3/4-in. nominal-diameter Schedule 160, Type 316 stainless steel pipe. Both tungsten and thoriated-tungsten wires of 0.030-in. diameter were used as the cathode. Chromel-Alumel thermocouples were placed in the anode wall to obtain temperature measurements. Heat was removed from the system by means of cooling coils positioned above the liquid-sodium level on which the sodium vapors condensed. This system was pressurized with an argon-gas blanket.

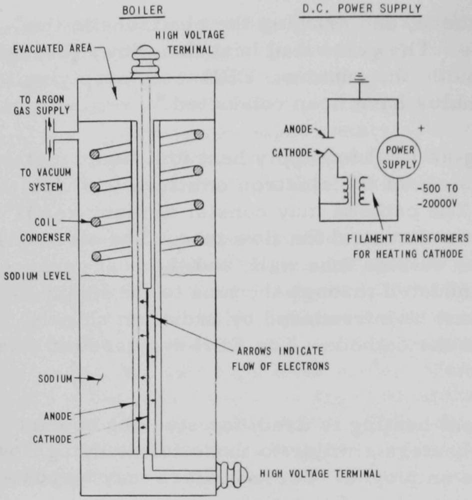

Fig. 1. Schematic Diagram of Previous EBH Experiment

This experiment was operated for more than 1000 hr using both tungsten and thoriated-tungsten emitters. Uniform heat fluxes over the 16-in. heated length ranging up to 3.71×10^5 Btu/hr-ft (21.7 kW) were supplied, and sodium temperatures up to 1600°F were obtained.

Heat fluxes possibly ranging up to 10^7 Btu/hr-ft^2 may be obtained by using electron-bombardment heating. Factors that limit the maximum heat flux are the power-supply limitations and the thermal stresses in the tube (anode) wall.

However, there are many design problems associated with the building of a high-heat-flux EBH which will be used to heat liquid metals ranging up to 2100°F. The following sections of this report point out some of the design considerations pertinent to the building of a successful EBH and discuss the successful operation of a high-heat-flux EBH.

III. EBH DESIGN CONSIDERATIONS

There are two modes of EBH operation. First, the heater may be operated in the space-charge-limited region. Second, it may be operated in the emission-limited region. The geometry of the heater and the magnitude of the anode voltage are the primary factors that determine the mode of operation. If the anode voltage is high enough for a given geometry, the electrons emitted by the cathode will be drawn to the anode at a rate equal to the emission rate. In this case, the anode current is limited by the electron emission rate of the cathode, and this region is called the emission-limited region.

If the anode voltage is lowered to a point where the electrons are emitted at a rate greater than the electron removal rate to the anode, the electrons congest around the cathode forming a space charge. The anode current is then limited by the anode voltage, and this region is called the space-charge-limited region.

Most electron tubes operate in the space-charge-limited region. The anode voltage controls the emission current in a diode, and the grid voltage controls the emission current in a triode. The requirements of an EBH must be considered, and the most suitable mode of operation and method of control chosen for the application.

An EBH can operate only in an evacuated environment. If the experimental apparatus to be heated can also be contained in a vacuum, a separate containment may not be necessary. A vacuum better than 10^{-5} Torr must be achieved for proper EBH operation, for the presence of even small amounts of gas can have a destructive effect on emitters.

Movement of the test apparatus during EBH operation may bend or break the filaments, especially the extremely brittle carburized thoriated-tungsten filaments. The movements that could occur are due primarily to thermal-expansion problems and vibrations. Hence, a method of heater removal and repair should be incorporated in the design.

The selection of cathode material for an electron tube is based on many factors, including geometry and operating power level. The three most commonly used electron emitters are tungsten, thoriated tungsten, and oxide-coated cathodes. Because of the high voltages and high temperatures associated with the high heat fluxes required in boiling-liquid-metal experiments, pure tungsten and thoriated-tungsten emitters appear to be more feasible than oxide-coated emitters for this application. Figure 2 shows the emission characteristics of tungsten and thoriated tungsten as predicted by Richardson's equation. Thoriated tungsten emits more electrons than does tungsten at the normal operating temperatures. Figure 2 does not show the effect of accelerating voltage upon emission current.

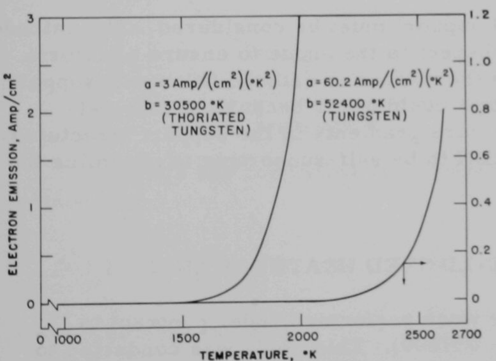

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Fig. 2. Electron Emission of Tungsten and Thoriated Tungsten

Figure 2 also shows that the electron emission per unit area increases with increasing temperature; thus, the larger the area emitting electrons, the lower the temperature required for a given heat flux. For a fixed temperature, the total number of electrons leaving a cathode of a given material is directly proportional to the cathode area. It is desirable to operate an electron emitter at a lower temperature so that the emission current may be better controlled; thus, for high-heat-flux applications, a cathode having larger emitting area may be superior to a cathode of smaller area. Hence, the cathode shape is of considerable importance in the design of an electron-bombardment heater, especially for operation in the emission-limited region.

Thoriated tungsten is carburized to give long, stable life. Carbon will be evolved during the life of the heater, principally in the form of carbon monoxide (CO). Thermodynamic calculations show that one 7.5-in. heater section will yield approximately 1 μg of carbon per hour of operation. This rate could cause objectionable carburization of some of the material from which the experiment is constructed. Thoriated tungsten that has not been carburized may be used if this rate of evolution is objectionable. Provisions must also be made for heating this filament to higher temperatures for brief periods (sometimes called flashing) to reduce some of the thoria, and promote its diffusion to the surface of the wire.

Since the anode tube contains the liquid metal, this tube material must be compatible with the liquid metal as well as being a satisfactory anode material. Of the available materials, the most satisfactory for this application are the Series 300 stainless steels and the refractory metals.[5] The high heat fluxes obtainable from EBH's can cause severe thermal stresses in the anode wall. The wall thickness, the strength of the material, and the thermal stress across the wall must be considered in the design. Operating the anode at a temperature high enough to stress-relieve the anode structure may prevent rupture at the very high heat fluxes.

The methods of structural support must be considered. The cathode must be located accurately with respect to the anode to ensure a uniform power distribution. In addition to the method of cathode (filament) support, one must consider the problems that could occur because of thermal-expansion differences and temperature gradients in the support structures. It is also possible to design the EBH to be self-supporting to minimize the stresses in the anode.

IV. SPACE-CHARGE-LIMITED HEATER DESIGN

This section describes the work performed under contract to Argonne National Laboratory (No. 057800). This study was conducted to determine the optimum design of a particular EBH. The study evaluated conceptual designs of a diode and a triode, both operating in the space-charged-limited region. The following characteristics were evaluated for each of these concepts:

1. Voltage-current characteristics
2. Power capability
3. Mechanical stability
4. Thermal stability
5. Materials compatibility
6. Cathode material selection

A. Diode Concept

To achieve a heat flux of 10^7 Btu/hr-ft^2 across a cylindrical surface which is 5/16-in. ID with a total power of 150 kW, the maximum heated length was determined to be 7.5 in. With this information, and the assumed nominal OD of 0.5 in. for the cylinder to be heated, the voltage and current of the diode were computed as a function of cathode radius for space-charge-limited operation. These calculations are summarized here, and the results are presented in Fig. 3.

Maximum heat flux	10^7 Btu/hr-ft^2 = 3150 W/cm^2
Maximum power	150 kW
Length of section	7.5 in.
Outside diameter of section (nominal)	0.5 in.
Power per unit length	20,000 W/in.

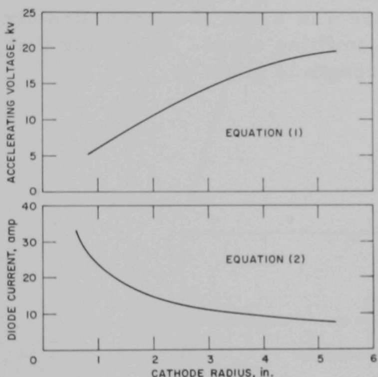

Fig. 3

Accelerating Voltage and Diode Current vs Cathode Radius

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Child's law for cylindrical diode current corrected for filamentary cathode is

$$I = GV_a^{3/2},$$

where the perveance is

$$G = \frac{f_c \times 14.66 \times 10^{-6} L}{r_a(-B)^2} = \frac{0.7 \times 14.66 \times 10^{-6} \times 7.5}{0.25(-B)^2}$$

and B^2 is a function of r_c/r_a (cathode radius/anode radius). The total power is $P = IV_a$.

Combining the above three equations yields the following:

$$V_a^{5/2} = \frac{P}{G},$$

$$V_a^{5/2} = \frac{1.5 \times 10^5 (0.25)(-B)^2}{0.7 \times 14.66 \times 10^{-6}(7.5)},$$

$$V_a^{5/2} = 4.87 \times 10^8 (-B)^2, \tag{1}$$

and

$$I = \frac{150{,}000}{V_a}. \tag{2}$$

The emitting area and total current should be adjusted to keep the current density below 0.3 Amp/cm^2. Figure 4 is a plot of current density as a function of cathode radius for two emitting areas. Assuming that space charge is not present, the field strength is given by

$$E(r) = \frac{V_a}{r \ln\left(\frac{r_c}{r_a}\right)}. \tag{3}$$

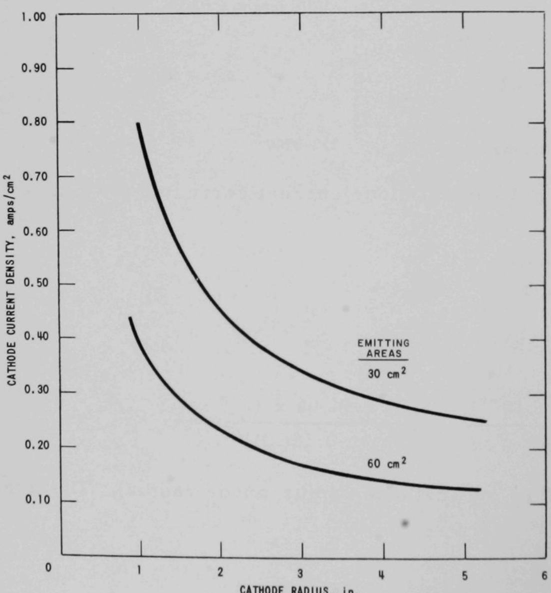

Fig. 4

Cathode Current Density vs Cathode Radius

Figure 5 is a plot of the field strength at the anode as a function of cathode radius for a constant power density at the anode. A field strength of 25 V/mil is considered conventional for high-power electron tubes.

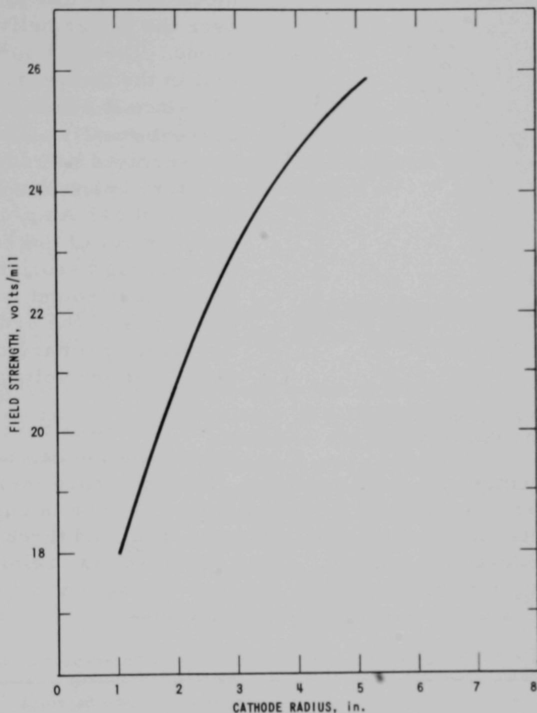

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Fig. 5. Field Strength at Anode vs Cathode Radius

On the basis of these calculations, the following design has been chosen:

Anode radius	0.25 in.
Cathode radius	1.8 in.
Maximum current	15 Amp
Maximum current density (cathode)	0.247 Amp/cm^2
Cathode	20 wires of 0.020-in. diameter, equally spaced, 60-cm^2 area
Perveance (one section)	15×10^{-6}

This calculated current-voltage relationship and the power capability for this design are shown in Fig. 6. These plots are based on space-charge-limited operation where the diode voltage has primary control over the power delivered to the anode. There is some slight control in the temperature of the cathode since it controls the available current density. This control can be exercised by reducing the temperature below that required to deliver 0.247 Amp/cm^2. Temperature control of the cathode has thermal lag associated with it, and since the filament is directly heated, this lag is of the order of seconds. Therefore primary control rests with the diode voltage.

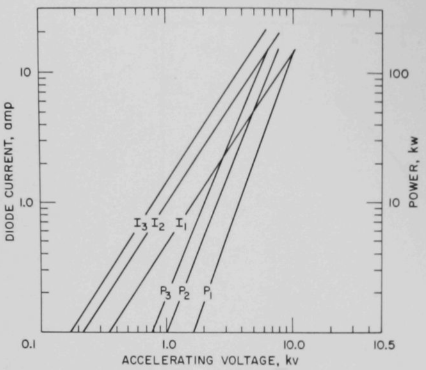

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Fig. 6. Diode Current and Power vs Accelerating Voltage

A lower heat flux over a longer section can be achieved by activating incremental 7.5-in. sections. The perveance increases linearly with the number of sections. A total of three sections is contemplated. Table I presents the characteristics for one, two, and three sections having the same cathode-anode spacing. The current-voltage relationships and power capability for these multiple sections are shown in Fig. 6 where the subscripts indicate the number of active sections.

TABLE I. Characteristics of One-, Two-, and Three-section Diode

	One Section	Two Sections	Three Sections
Overall Characteristics			
Length, in.	7.5	15	22.5
Perveance	15×10^{-6}	30×10^{-6}	45×10^{-6}
Maximum power, kW	150	150	114
Current, Amp	15	20	23
Voltage, kV	10	7.55	6.45
ID area of anode, cm^2	45.5	95	143
Power density at ID of anode, W/cm^2	3150	1575	797
Flux at ID of anode, Btu/hr-ft^2	10^7	5×10^6	2.5×10^6
Characteristics at Heat Flux of 10^6 Btu/hr-ft^2			
Power, kW	15	30	45
Current, Amp	3.74	7.5	11.2
Voltage, kV	4.0	4.0	4.0
Characteristics at 1% of Maximum Flux			
Heat flux, Btu/hr-ft^2	10^5	5×10^4	2.5×10^4
Power, kW	1.5	1.5	1.14
Current, Amp	0.94	1.2	1.25
Voltage, kV	1.6	1.25	0.91

B. Triode Concept

The current-voltage relationship for a triode is given by

$$I = G\left(V_g + \frac{V_a}{\mu}\right)^{3/2},$$

where G is the perveance, V_g is the grid bias, and μ is the amplification factor of the triode. The perveance and amplification factor are functions of the geometry. For a given geometry and a given anode voltage, the current to the anode may be cut off by choosing

$$V_g = -\frac{V_a}{\mu} = V_{co},$$

where V_g is called the cutoff voltage. The grid voltage can exercise complete control over the power delivered to the anode.

Varying the grid voltage permits the anode power or heat flux to be varied over wide and complex cycles. The amplification factor can be chosen to make the cutoff voltage a small fraction of the anode voltage. The characteristic curves plotted in Fig. 7 show the relationship between anode current and grid-bias voltage for a series of anode voltages. This graph represents a single triode section 7.5 in. long with an amplification factor of 30 and a perveance of 1.5×10^{-3}. Figure 8 presents the power available in this triode. Variations of two orders of magnitude in anode power can be achieved by changing the grid voltage a few hundred volts. The current densities required for this operation are of the same order as those required for the diode operation.

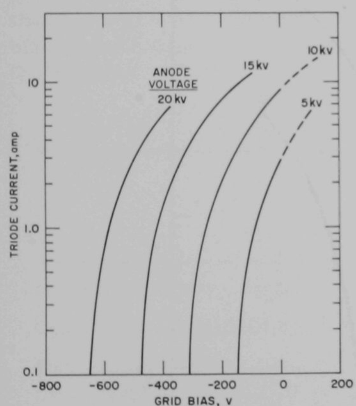

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Fig. 7. Characteristic Curves for a Triode

The perveance of a cylindrical triode is given by

$$G = \frac{1.466 \times 10^{-6} L}{r_g \beta_{cg} \left\{1 + \frac{1}{\mu}\left[\frac{r_a}{r_g}\left(\frac{\beta_{ca}}{\beta_{cg}}\right)^2\right]^{2/3}\right\}^{3/2}},$$

where r_g and r_a are grid and anode radii and the combination subscripts indicate that β^2 is to be determined by the ratio of the radii of the electrodes indicated by the subscripts. A formula that is valid over the complete range of variables does not exist for the amplification factor of a triode. Hence, various approximations are used over limited ranges of electrode dimensions in specific geometries. The most useful formula for the inside-anode geometry of the EBH is given by

$$\mu = \frac{-2\pi\left(r_g - r_a\right)}{s\ \ell n\left(2 \sin \frac{\pi r_g}{s}\right)},$$

where s is the space between grid wires.

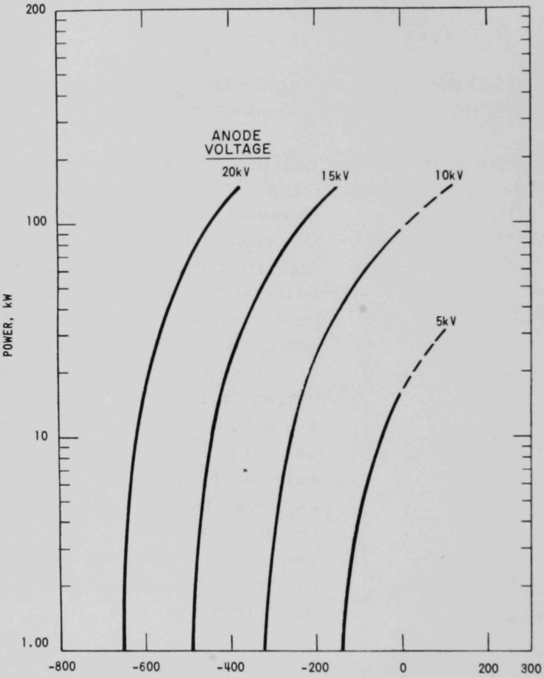

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Fig. 8. Triode Power Output

In general, the amplification factors and perveance achieved in practical designs are lower than those calculated from the formula. An amplification factor of 30 and a perveance of 1.5×10^3 can be achieved with a triode of the following dimensions:

Anode radius	0.25 in.
Cathode radius	1.8 in.
Grid radius	1.5 in.
Space between grid wires, s	0.235 in.
Grid-wire diameter	0.020 in.
Number of grid wires	40

A useful triode design could be made simply by adding a grid (of radius 1.5 in.) to the diode design. The characteristic curves of Figs. 7 and 8 could probably not be achieved in practice, but the difference would not be significant. That is, the curves would be shifted slightly in slope and intercept, but the same power levels could be attained at nearly the same value of grid voltage and anode voltage.

C. Evaluation and Design

Table II presents typical operating data for three different filamentary cathodes at the required current density. The estimates of operating power include provisions for end losses from each filament. Thoriated tungsten is preferred over tungsten in electron tubes because of its greater efficiency, that is, a greater electron density for a given heating power. This greater efficiency allows an overall reduction in heat which must be discharged from the system. Radiant energy from the filament contributes to the total power.

TABLE II. Typical Operating Data for Three Cathode Materials

	Carburized Thoriated Tungsten	Thoriated Tungsten	Tungsten
Current density, Amp/cm^2	0.25	0.25	0.25
Operating temperature, °C	1,750	1,900	2,200
Estimated heating power for a 0.02-in. wire 7.5 in. long, W	84	140	234
Current, Amp	12	14	18
Voltage, V	7	10	13
Total power for 7.5-in. section, W	1,680	2,800	4,680
Total power for three sections, W	5,040	8,400	14,040
Half of maximum anode current per wire, Amp	0.375	0.375	0.375

The energy required to heat the cathode to the operating temperature will be dissipated primarily by thermal radiation and to a lesser extent by conduction. The radiated energy is available for heating, but the conducted heat is not useful for that purpose. The radiant energy incident on the anode cannot be determined directly. This energy will be absorbed by all other elements of the heater such as grids, supports, envelope, etc. All the energy will be removed from the system by the flowing liquid metal or by the water-cooled vacuum envelope. Thermal-expansion mismatch or thermal fatigue could cause faulty operation or even catastrophic failure. Table III shows some estimates of the energy and temperature distribution. The energy radiated by the filament is significantly greater than that radiated by the heated anode, and the contribution of both has been considered.

TABLE III. Estimates of Energy and Temperature Distribution

	Carburized Thoriated Tungsten	Tungsten
Energy radiated from the tube, W/cm^2 (1250°C)	5	5
Energy radiated by the filament, W/cm^2	24	63
Energy conducted from each section, W	240	900
Radiant energy absorbed by grid, W/cm^2	3.85	9.55
Grid temperature required to reradiate all energy, °C	1329	1670
Radiant energy absorbed by heat shield, W/cm^2	2	5
Temperature of heat shield required to reradiate, °C	1013	1265

The sectional concept of the heater does not allow for a sectional structure on the grid. One grid structure must extend over the entire 22.5 in. of a three-section heater. Using 0.020-in.-diam wire for grid bars over this distance means that very little heat will be expelled from the grid by conduction, and the grid wire will approach the cathode temperature. Cooling the grid by adding cross bars and using extra heat sinks does not improve this condition without enlarging the cross-sectional area of the grid and therefore increasing the screening factor. A high grid temperature must therefore be accepted. This presents difficulties from mechanical-structure considerations. At 1500°C, for instance, a tungsten grid wire 24 in. long will expand nearly 0.25 in. If anything restricts this simple elongation, the grid wire will bend and change the spacing between the cathode and grid and seriously alter the perveance and the amplification factor.

Because of heat conduction, the filament support structure becomes a heat sink for the filament. The support member will not be attached to a heat sink of the vacuum chamber and will approach some equilibrium temperature. Since this support member must maintain tension on the filament, the temperature profile is important. Molybdenum, the material intended for this application, recrystallizes above 900°C and should be kept well below this temperature. Rather than base this critical design aspect on calculation, a bell jar test was conducted with a mockup of a filament and support structure. In the critical region of the support structure, temperature was less than 500°C. Therefore, a technique for supporting the filament wire with the necessary tension is definitely possible.

Heat shields, which serve the dual purpose of ion collectors, can dissipate all absorbed radiant energy by emitting thermal radiation at about 1000°C. This temperature will establish the interior ambient temperature. All exterior heater-support structures will be below this temperature and are expected to be thermally stable.

The heater must be mounted on, and carefully aligned with, the tubular anode. If the thermal expansion of the anode is very close to that of high-purity alumina (94% Al_2O_3) ceramic, expansive contact between the tube and the heater can be accommodated by a sliding metal-ceramic fit. This type of joint should permit unrestricted thermal cycling and provide good electrical insulation.

Mechanical stability has been studied with two experiments in mind: first, the requirement of being able to install and remove the heater without disturbing the anode; second, the requirement of maintaining alignment with the tube to provide the required heating uniformity.

Two designs were considered for ease of installation: (1) the "clamshell" approach; (2) the "C" shape with an opening slot sufficiently large to accommodate the tubular anode. Each of these designs calls for a stacked series of ceramic and metal parts which can be brazed or bolted together to form a rigid structure. The C-shaped structure may have a vertical cut equal to the filament and grid-bar spacing without affecting the electrical characteristics. The C-shaped structure can be sufficiently rigid so as to be set in place on the tube. The clamshell design has two halves that must be assembled as they are placed on the tube. The two halves can be interlocked and held together by brackets.

Each design therefore can fulfill the above requirements. The clamshell design affords the additional advantage of access to interior parts for inspection and repairs such as the replacement of broken filaments.

The performance of the heater assumes a uniform heat flux or power density. Nonuniformities will result if the heater does not conform to the design perveance at each point. Variations in interelectrode spacing caused by nonconcentric alignment will alter the perveance and power distribution. For the diode, the increment of change in spacing is inversely proportional to a change in those dimensions, as shown in the following equation:

$$\frac{dI}{dr_c} = \frac{G\,V_a^{3/2}}{r_c(-\beta^2_{ca})} = \frac{I}{r_c(-\beta^2_{ca})} .$$

The cathode-anode spacing is of the order of inches; therefore variations of the order of 0.010 in. will result in a 1% variation in current to the anode. This precision is achievable and measurable, and this uniformity is acceptable.

For the triode, the change in anode current is more dependent on changes in cathode-grid spacing than on grid-anode spacing, the form of the variation being similar to that of a diode, as shown in the following equation:

$$\frac{dI}{dr_g} = \frac{G\,V_a^{3/2}}{r_g(-\beta^2_{cg})} + \text{higher-order terms.}$$

The cathode-grid spacing is of the order of a fraction of an inch while the variations in this spacing are still of the order of 0.010 in., making variations of several percent in anode current quite possible. In a triode with a 24-in.-long grid, spacing variations may exceed 0.010 in. The filament may be spring-loaded and held in position reasonably well over a length of 7.5 in. The grid, being over three times as long as the filament and difficult to spring-load, presents alignment difficulties.

The principal advantage of the triode is its ability to control the power rapidly over wide and complex cycles. The most immediate requirement, however, is for a simple step function to higher or lower power levels. Responses of fractions of a second are possible for a diode or a triode simply by a switch.

This evaluation therefore recommends the diode for preliminary design because it is less sensitive than the triode to variations in interelectrode spacing while having equal capability to achieve the desired transients. Additional transient capability might be necessary for other applications. For example, studies of two-phase flow with exponential or sinusoidal power input could be required. These types of transient power pulses may be required to study some of the safety aspects pertinent to fast reactors. A triode which uses many diode parts could be designed and built for this application. The principal features of the design are shown in Fig. 9.

The basic design of the heater is modular, consisting of ceramic insulator assemblies, filament support rings, ion detector-heat shield assemblies, and assembly hardware. The ceramic assemblies consist of a ceramic cylinder cut into sections. The filament supports and ion-detector contact ring are held and indexed between the ceramic assemblies by rods. Mechanical rigidity is achieved through use of rods which hold the end plates securely together. Each section and assembly is made as a clamshell for assembly on the loop, and the two halves of the clamshell are mounted together by brackets.

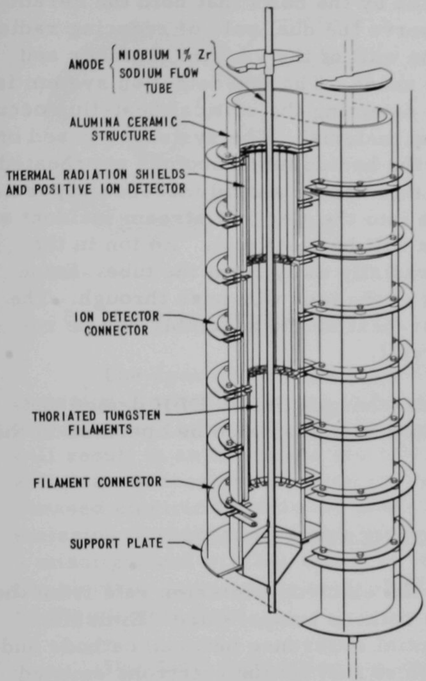

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Fig. 9. Pictorial Drawing of EBH Design

The weight of the heater is supported from the top end plate, relieving the weight burden from the niobium tube. The heater is held in alignment with the tubular anode by a ceramic disk on the top and one on the bottom. Ceramic is used to prevent possible seizing of the top guide to the anode. Since there will be minor abrasion of the tubular anode, a reinforcing sleeve should be used on that portion of the tube.

The individual spring-loaded straight-filament bar design has been selected as the most practical one from the standpoint of construction, uniformity of heating the anode, and ability to replace individual elements. The filament elements are straight lengths of wire, which are melted to form a ball at each end. The balled ends are held in a cup arrangement of the filament-support rings. Individual fingers of the filament-support rings provide the independent spring loading for each filament wire.

To achieve uniform heating of the anode, the filaments of adjacent sections of the heater must overlap each other to compensate for the loss of emission due to end cooling. This is achieved by staggering the 20 filaments of each adjacent section; i.e., on the two internal filament-support rings, filaments will alternately extend in opposite directions. The fingers will be bent alternately up and down to provide the desired overlap of the filaments.

The ion detector-heat shield assembly consists of a series of thin metallic sheets separated by narrow rods mounted just inside the ceramic insulator. The assemblies are supported by the bolts that hold the ceramic sections together. These assemblies serve the dual role of reducing radiation heat losses from the filament to the wall of the vacuum chamber and detecting positive ion current from the anode. The ion-detection system is a new concept that may prove useful in detecting the critical heat-flux occurrence or catastrophic failure of the loop material. The system is based on the concept that if a particular spot on the heated tube becomes overheated, evaporation of atoms and molecules in this region should increase appreciably and the evaporated atoms will move into the electron stream incident on the tube. The probability for ionization will be quite high. An ion in the high electric field will be accelerated radially away from the tube. Some ions will strike the filaments, but most of the ions will pass through. The rate of ion collection on the ion detector-heat shield assembly can be recorded using an external electronic circuit.

This section has discussed space-charge-limited EBH design and operation. However, the design presented here may also be operated in the emission-limited region.

V. EMISSION-LIMITED HEATER DESIGN

In the emission-limited region, the electron-emission rate from the cathode is determined primarily by the cathode temperature. Emission-limited operation occurs when the potential difference between cathode and anode (anode voltage) is sufficiently high so that all the electrons emitted by the cathode are drawn to the anode. The electron-emission rate for EBH operation in the emission-limited region is expressed by Richardson's equation,

$$i = aT^2e^{-b/T}.$$

The heat generated at the anode surface is the product of the emission current and the potential difference between the cathode and the anode.

Since the emission current in the emission-limited region is controlled by the cathode temperature, the diode concept appears most acceptable. The basic system geometries for flow through a tube and for annular flow are shown in Figs. 10 and 11, respectively. When an EBH is operated in the emission-limited region, the cathode must be at a uniform temperature so that a uniform heat flux is generated at the anode surface. Reference 1 examines the temperature distribution along the length of a wire cathode. These results indicate that the cathode surface temperature will be uniform, except for small end effects.

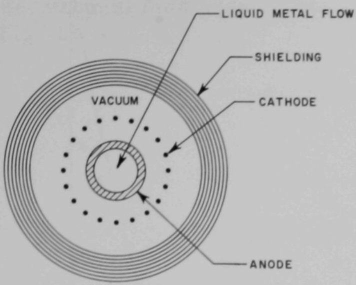

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Fig. 10. EBH Arrangement for Tube Flow

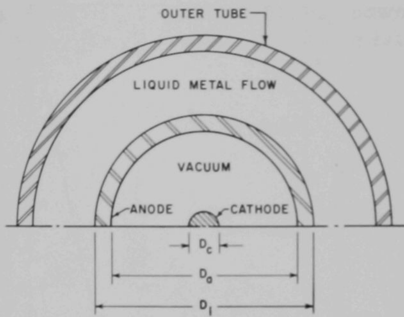

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Fig. 11. EBH Arrangement for Annular Flow

The spacing between cathode and anode is not as critical in the emission-limited region as in the space-charge-limited region. A misalignment in the cathode-anode spacing in the space-charge-limited region will result in an increased electric field on one side of the anode, which will draw excessive emission current to that side of the anode, and a decreased electric field on the other side, which will draw a much smaller emission current to that side of the anode. In the emission-limited region, a misalignment will not result in uneven emission from the cathode because the electron emission is controlled by the cathode temperature rather than by the electric field.

For EBH applications to annular flow, the cathode is located inside the tubular anode (as shown in Fig. 11). As noted in Section II (EBH BACKGROUND INFORMATION), testing at Argonne has yielded heat fluxes ranging up to 371,000 Btu/hr-ft^2 at the 0.608-in.-ID anode surface. Power-supply limitations have prevented operation at higher power levels (heat fluxes).

To analytically demonstrate the feasibility of an EBH for supplying high heat fluxes in annular flow, consider the heater shown in Fig. 11. Assume the following dimensions: $D_c = 1/8$ in., $D_i = 1/2$ in., and $D_a = 7/16$ in. Assume a potential difference of 20,000 V between cathode and anode. Figure 12 shows the heat flux being supplied to the liquid metal plotted as a function of cathode temperature for tungsten and thoriated tungsten. Heat fluxes above 10^6 Btu/hr-ft^2 may be obtained with both tungsten and thoriated-tungsten emitters for a system in which $D_c = 1/8$ in. and $D_i = 1/2$ in. It is also evident that higher heat fluxes may be obtained with thoriated-tungsten emitters than with tungsten, and that thoriated-tungsten emitters operate at lower temperatures than tungsten emitters. In this analysis, the electron emission was calculated from Richardson's equation; in practice, the emission current may be somewhat higher due to the field emission caused by the potential difference between cathode and anode.

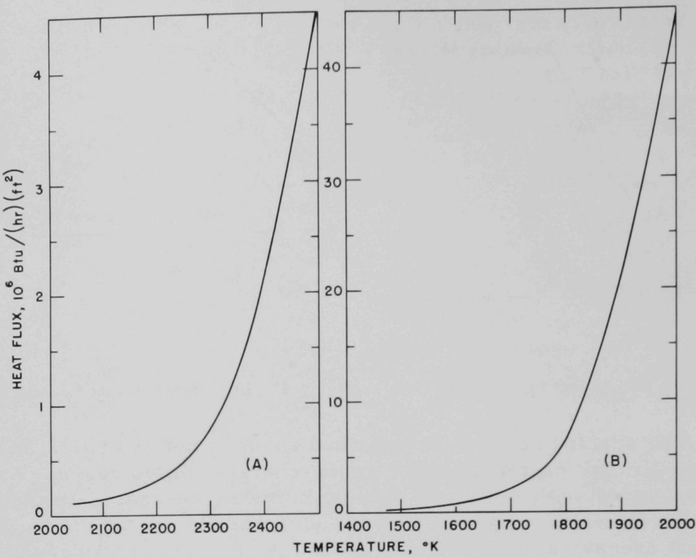

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Fig. 12. Heat Flux vs Temperature for (A) Tungsten and (B) Thoriated-tungsten Emitters

Having the filaments (cathode) surround the anode enables higher heat fluxes to be supplied to the anode than in an annular flow design. These higher heat fluxes are due primarily to the larger cathode area for obtaining higher emission currents, and a larger spacing between cathode and anode for obtaining higher potential differences between cathode and anode.

The physical structure of the emission-limited heater design is similar to that of the space-charge-limited design. The principal differences are in the electrical circuitry and control. The cathode voltage for the emission-limited heater is constant. The filament current is varied to increase or decrease the filament temperature, which controls the electron flow from cathode to anode. Controlling the filament temperature controls the power delivered to the anode.

VI. EXPERIMENTAL APPARATUS

A pictorial drawing of the EBH that has been designed and built, and is being tested at Argonne, is shown in Fig. 9. The EBH design has been discussed in Sections IV and V of this report.

Figure 13 shows a pictorial drawing of the EBH, shielding, power leads, vacuum feedthrough, etc. All the major EBH components are labeled in Fig. 13.

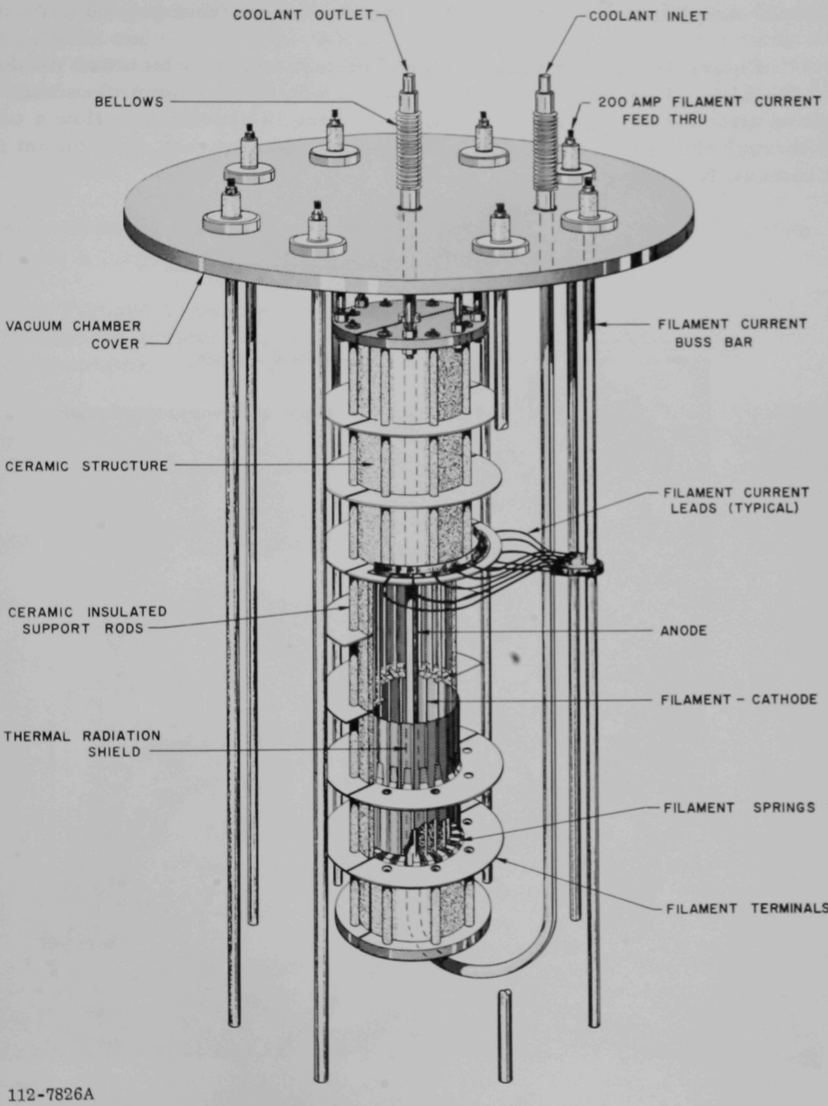

Fig. 13. Pictorial Drawing of Test EBH

Since the anode is at ground potential and the filamentary cathodes are at a negative 20 kV, the filament transformers must stand off the cathode voltages from ground. In addition, the filament current conductors which lead into the vacuum chamber must carry a relatively high current (200-400 Amp) and also stand off the cathode voltage from ground.

Figure 14 shows a vacuum-chamber test facility which was used to test the EBH. This facility is a 2-ft-diam x 4-ft-long vacuum chamber, with an attached 500-liter/sec ion pump. There is provision to flow a coolant through the center of the EBH. Depending upon the test, the coolant may be sodium, NaK, or water.

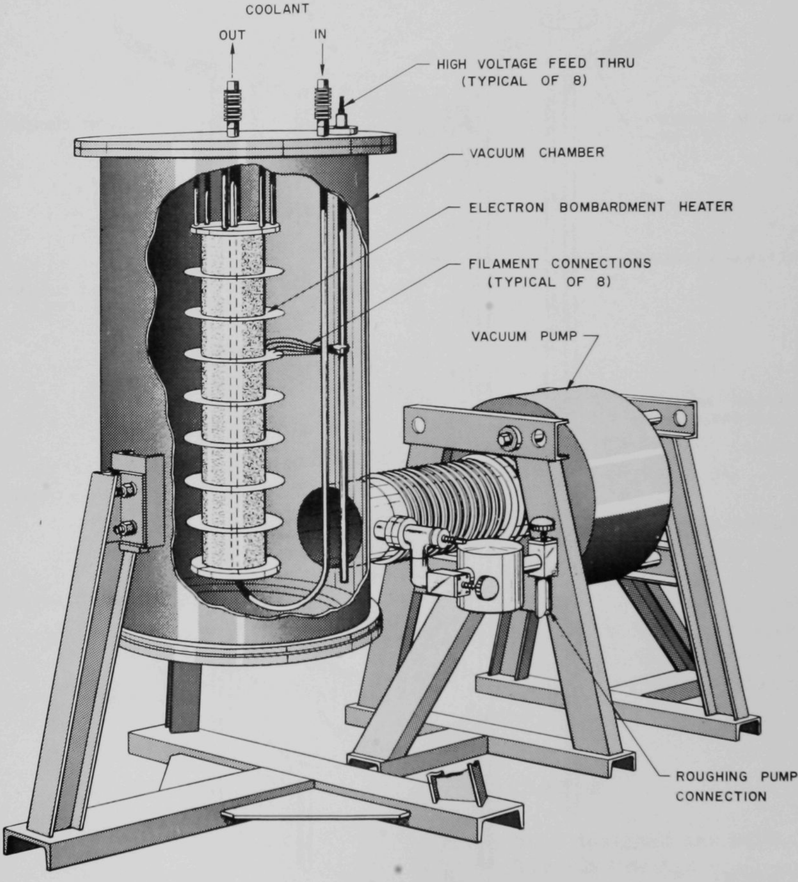

Fig. 14. Vacuum Chamber Test Facility

Since the anode temperature has an insignificant effect upon the operation of the EBH, water was selected as the coolant for the test experiment. The reason that the anode temperature has an insignificant effect upon the emission characteristics of EBH's using either tungsten or thoriated-tungsten filaments is that the only mode of heat transfer between the cathode and the anode is thermal radiation. Hence the radiation heat transfer between cathode and anode is influenced by the anode temperature, as indicated in the expression

$$q_{c \rightleftarrows a} \propto T_c^4 - T_a^4 .$$

Hence, when $T_c > T_a$, $T_c^4 >>>> T_a^4$, and the anode temperature (T_a) does not have a large effect upon the cathode temperature.

Figures 15 and 16 are photographs of the EBH, showing the uncarburized-thoriated-tungsten filaments, the molybdenum shield, the Al_2O_3 insulator, and the tubular anode.

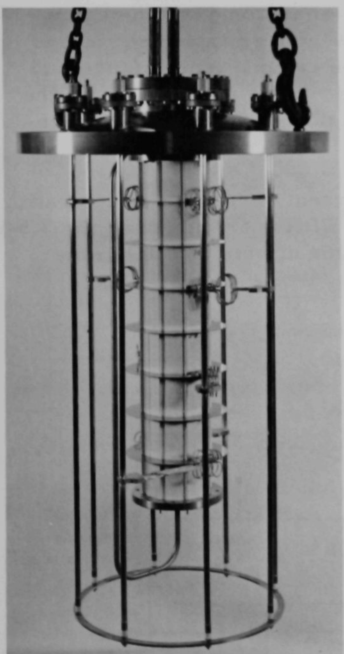

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Fig. 15. Photograph of Assembled EBH

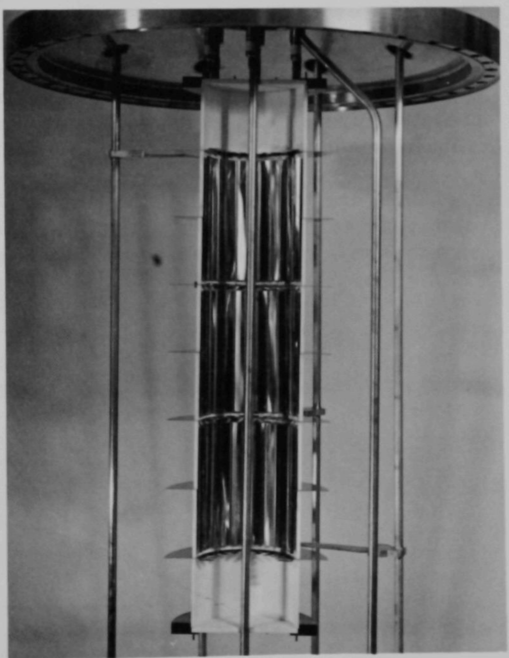

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Fig. 16. Photograph of Half-section of EBH

VII. EXPERIMENTAL RESULTS

The EBH experiment has been operated for more than 700 hr. Heat fluxes beyond 2.5×10^6 Btu/hr-ft^2 have been supplied over a 22.5-in. length and over a 7.5-in. length to water flowing in a 0.500-in.-OD, 0.430-in.-ID tube. Higher heat-flux levels could not be attained with this experimental setup because these heat fluxes were within 10% of the critical heat-flux occurrence. The emission characteristics of this EBH are shown graphically in this section.

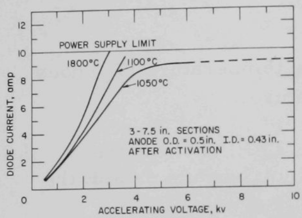

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Fig. 17. Diode Current vs Accelerating Voltage for 22.5-in.-long EBH Operation

Figure 17 shows the diode current versus accelerating voltage for uncarburized-thoriated-tungsten filaments in this EBH operating over the 22.5-in. length. In the space-charge-limited region, the electron-emission current is controlled by the accelerating voltage and not affected by cathode temperature. (The cathode temperature is controlled by the cathode heating power.) However, in the emission-limited region (horizontal lines), the emission current is controlled by the cathode temperature and the accelerating voltage does not affect the emission current. As expected, the emission current increases with increasing cathode-heating power.

Figure 18 is a plot of the emission current versus the accelerating voltage for various cathode temperatures for EBH operation over the 7.5-in. length. These curves show essentially the same effects as the curves

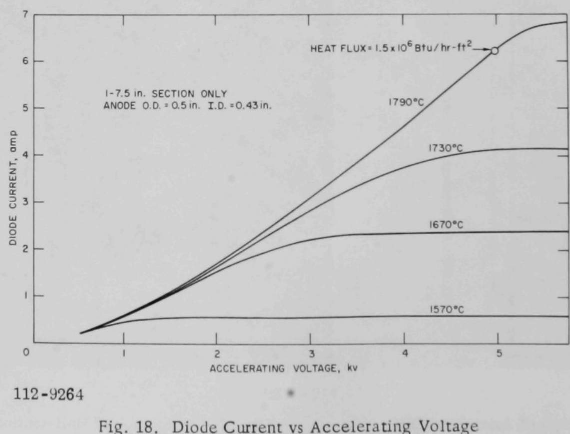

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Fig. 18. Diode Current vs Accelerating Voltage for 7.5-in.-long EBH Operation

in Fig. 17, except that the cathode temperature as well as the cathode heating power are shown. Operation in both the space-charge-limited and emission-limited regions is shown. The cathode temperature was measured by using an optical pyrometer.

Figure 19 shows the saturation current plotted against the cathode temperature for unactivated, uncarburized-thoriated-tungsten filaments in the EBH. Hence, this curve shows the points of transition into the emission-limited region at various cathode temperatures.

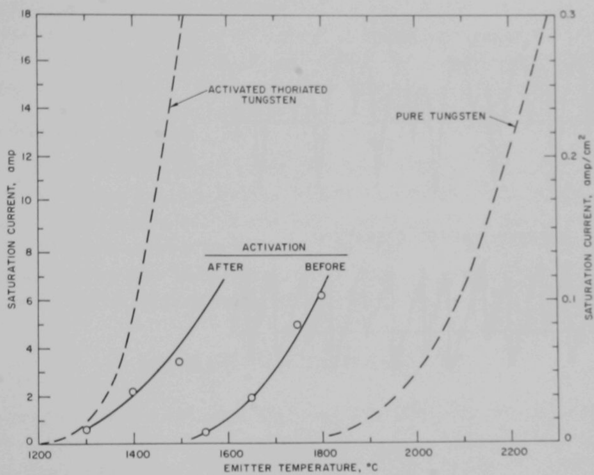

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Fig. 19. Saturation Current vs Cathode Temperature for EBH

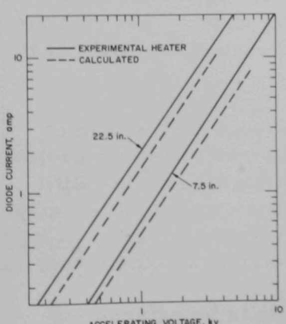

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Fig. 20. Diode Current vs Accelerating Voltage for Space-charge-limited EBH Operation

Figure 20 is a plot of both the experimentally measured and calculated curves of diode current versus accelerating voltage for space-charge-limited operation. Curves for both the 22.5-in.-long and 7.5-in.-long EBH operation are shown. The experimentally measured diode currents are higher than the calculated diode currents during both the 22.5-in.-long and the 7.5-in.-long EBH operation.

Figure 21 shows the current waveforms during both space-charge-limited and emission-limited operation. A more stable waveform exists during space-charge-limited operation than during emission-limited operation. The more stable waveform in the space-charge-limited region is achieved because the number of electrons leaving the cathode is controlled by the accelerating voltage, whereas, in the emission-limited region, the diode current is controlled by the cathode temperature (cathode heating power), which changes slightly because of variations in line voltage.

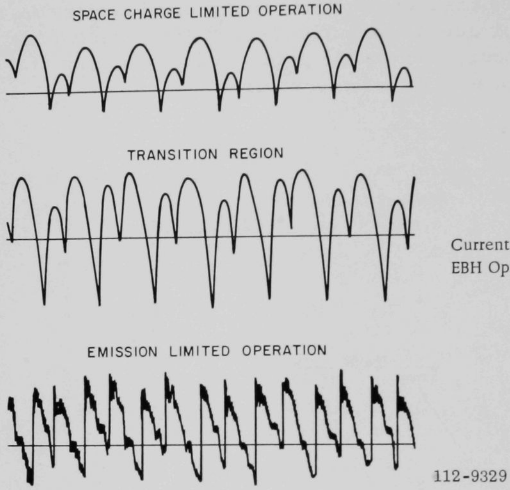

Fig. 21. Current Waveforms during EBH Operation

VIII. DISCUSSION

The information contained in this report has shown that electron-bombardment-heating techniques are capable of supplying high, uniform heat fluxes to high-temperature liquid metals. These experiments have demonstrated that EBH's can supply heat fluxes well above 2.5×10^6 Btu/hr-ft^2. Also, Fig. 13 shows an EBH that has been designed to supply heat fluxes ranging up to 10^7 Btu/hr-ft^2.

Because of the limited operating experience with EBH's, some design problems may occur. Hence the building and operating of a prototype heater may prove pertinent to the building of a high-heat-flux EBH for a particular application. Some areas in which design difficulties may occur are: filament support, temperature profiles, anode integrity at high heat fluxes, and anode concentricity and the associated nonuniform heat flux.

The vacuum-chamber test facility at Argonne is being used for testing the EBH discussed in this report as well as other EBH's. Specific development will be in the area of small-diameter EBH's that can be used to simulate nuclear fuel rods in fast breeder reactors. The study of the heat transfer from both single fuel pins and clusters of fuel rods is pertinent to the fast-reactor safety program in the U.S. A reliable EBH, which can be used for both steady-state and transient operation at high heat fluxes, will enable the simulating of both the pump-coast-down accident and the excess-of-reactivity accident. Since these fuel rods will probably range from 1/4 to 3/8 in. in diameter, the specific design problems will be close tolerances at high temperatures and material compatibility. Electron-bombardment heaters of this type are being designed and built to supply the necessary high heat fluxes for fast-reactor safety studies.

Testing with the present tube-flow-type EBH has yielded heat fluxes ranging beyond 2×10^6 Btu/hr-ft^2 over a 22.5-in.-long, 0.430-in.-ID tube and over a 7.5-in.-long, 0.430-in.-ID tube. These steady-state heat fluxes are being supplied during continuous operation in both the emission-limited and space-charged-limited regions.

The present limitation upon the heat flux is the critical heat-flux occurrence. In these initial tests, water is being used as the coolant, and the above heat fluxes approach the critical heat-flux occurrence for the heated tube. Modifications to both the coolant system and the power supply are being planned so the heat flux range may be extended beyond the previously obtained limits in future EBH tests.

ACKNOWLEDGMENTS

We wish to acknowledge the work of Mr. Bruce Barnaby and Mr. Harlow Lloyd of EIMAC Corporation under contract to Argonne National Laboratory (No. 057800). The work is included in Section IV (SPACE-CHARGE-LIMITED HEATER DESIGN). Also, we acknowledge the work of Mr. Keith Stair in assembling and operating the apparatus.

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